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Effect of Microstructure on Mechanical Properties of Cornstalk

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Abstract. The research on the mechanical properties of cornstalk, a natural biomass, is of great significance in the fields of deep-processing and reuse, preparation of biomimetic materials and so on. In this study, an electronic universal material testing machine was used in the macroscopic mechanical property test of cornstalk radial compression, axial compression, cutting, and three-point bending. The microstructure of cornstalk rind and cornstalk pith was characterized by scanning electron microscopy (SEM), and the effect of microstructure on mechanical properties of cornstalk was revealed. Mechanical properties of cornstalk mainly depend on the pith in radial compression, and mainly depend on the rind in other loading modes, and the relationship between the mechanical properties and the microstructure of corn stalk is revealed from the microscopic scale.

Keywords. Biomass, cornstalk, microstructure, mechanical properties

1. Introduction

Corn is the third-largest food crop in the world after rice and wheat. Compared with rice and wheat, corn has more by-products after harvest, and the problems of environmental pollution caused by straw burning, changes in soil moisture caused by re-turning straws to the field, and changes in ground temperature have become major problem that plagues agricultural production [1, 2]. Cornstalk is an important renewable biomass resource, which can usually be crushed and further processed into organic fertilizer, silage, etc. after harvesting [3]. In addition, cornstalks are also rich in high-quality plant natural fibers, which have broad application prospects in the textile industry, construction industry, new composite material manufacturing, and other fields [4-6]. In the numerous deep-processing and utilization links of cornstalks, mechanical extrusion, bending, crushing and other processes have almost become the necessary processing stages.

With the rapid development of modern technology, there are more and more studies on the microscopic scale of plants with the help of modern instrumental analysis technology [7, 8]. In the study of cornstalks, Zhao carried out the surface characterization of the physicochemical properties of ultra-fine powder of cornstalks with different particle sizes [9]. At present, there are limited studies on the interaction between the microstructure and mechanical properties of cornstalks, and a large number of studies

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mainly focus on by-products such as corn bract and corn cob. Zou used SEM, FTIR and other techniques to characterize the macro-geometric parameters, microstructure and composition of the three parts of corn cob pith, wood ring and glume, and carried out axial compression, radial compression, three-point bending and impact tests [10]. Li described the physical tensile properties of maize bracts of two maize cultivars in the whole harvest cycle, recorded the surface morphology and cross-sectional morphology of the bracts using SEM, and expressed the fracture mechanism of leaves and leaf sheaths from the perspectives of physiology and morphology, providing theoretical guidance for the design and optimization of corn peeling device [11]. All in all, it is of great significance to carry out related research on the biomechanical properties and microstructure of plant stalks for its comprehensive and efficient utilization in post-harvest processing.

2. Materials and Methods

The cornstalks used in the test were obtained from corn plants that had no pests and diseases and no mechanical damage after the corn was harvested, and the part between the fourth and fifth nodes below the corn was selected. The selected corn variety is *Zhuoyu299*, and the planting site was Longyang District, Baoshan City.

2.1. Physical Experiments and Methods of Mechanical Properties

In the post-harvest stage of cornstalks, mechanical rubbing, extrusion, bending and cutting become the main damage forms in the deep-processing process. In the mechanical properties experiment, the electronic universal material testing machine (WD-E, GRANDTRY, Guangzhou, China) was equipped with a force sensor (STC-100 Kg, VISHAY, Tianjin, China), computer and operating software were used to complete the test. In all experiments, the loading speed of the electronic universal material testing machine was set to 40 $mm \cdot min^{-1}$. The test contents mainly include compression, cutting and three-point bending. The compression test was divided into radial com-pression and axial compression, the test platform and operating standards of the cut-ting test were selected from the same test fixtures, blades and parameters as Zhao [12], and for the three-point bending test, the distance between the two fixed supports fulcrums was selected as 80 mm.

2.2. Microstructure Imaging

After ultrasonic cleaning of the experimental samples, 10 mm ×10 mm samples were cut respectively. Scanning electron microscopy (SEM, Gemini 500, ZEISS, Ger-many) was used to observe and photograph the cornstalk surface (outside of cornstalk rind), inside of cornstalk, pith, and cross-section rind incision and pith incision. During the imaging process, the detector type was SE, set the electron beam intensity to 2.00 keV and the magnification to be 100-20 k times.

3. Results and Discussion

3.1. Mechanical Properties Analysis

The experimental results of the mechanical properties of cornstalks under static loading conditions are given in Figure 1. It can be seen from Figure 1 that the compressive strength and flexural strength of the whole cornstalk are the highest, and the peak force and cutting energy required for cutting are the largest. During radial compression, the compressive strength mainly depends on the pith. In the process of axial compression, the compressive strength mainly depends on the rind. Similarly, the peak cutting force and cutting energy also mainly depend on cornstalk rind, and the flexural strength also mainly depends on the cornstalk rind. This is the primary source of the axial compressive strength, cutting force, cutting energy and flexural strength of the whole cornstalk.

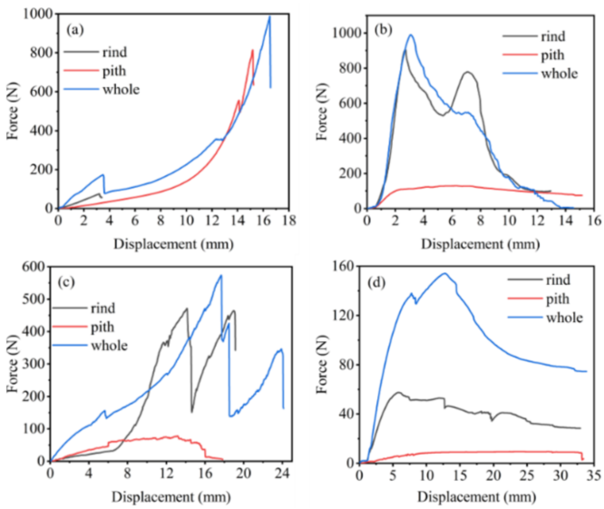

Figure 1. Results of mechanical properties test. (a): radial compression; (b): axial compression; (c): cutting; (d): three-point bending.

Further analysis found that in the process of radial compression (Figure 1a), when the displacement reached about 3 mm, the cornstalk rind reached the ultimate strength, and ruptured along the fiber texture, forming a small peak, As the displacement increases, the cornstalk pith was always compressed and elastically deformed until it yields when the loading load is nearly 800 N. During the axial compression process (Figure 1b), when the displacement reaches about 3 mm and the loading load is about 900 N, the cornstalk rind reaches the yield state and fracture occurs in the axial direction. Continue to load, when the displacement reaches about 5.5 mm, Radial passive loading, until the loading load rises to about 800 N, and the cornstalk rind was radially fractured, However, the bending deformation of cornstalk pith was always at a low force level until the deformation is too large and ejected the test bench, without yield failure. From the cutting experimental results in Figure 1c, the cutting peak force and cutting energy mainly depend on the cornstalk rind. When the loading load reaches about 50 N, the cornstalk rind begins to deform greatly due to the hollow cylindrical shape of the cornstalk rind, until the loading load reaches about 450 N, the first rupture along the fiber occurs, and the cutting starts with continuous loading, and the peak cutting force was also about 450 N. Due to its special mechanical properties, the cornstalk pith can quickly enter the knife, easily cut off, the cutting process is stable, and the peak cutting force is always kept at a low level. The three-point bending results (Figure 1d) show that the cornstalk rind fractures along the radial direction when the loading load reaches about 40 N. When the loading load reached about 150 N, the whole cornstalk fractured along the radial direction. In the three-point bending test of the cornstalk pith alone, a large deformation similar to the axial compression occurred, and the yield failure didn't occur until it slipped away from the fixed support.

It is worth noting that in the radial compression, axial compression, cutting and three-point bending experiments, the yield strength was always dependent on cornstalk rind for all tests except radial compression. This is mainly due to the high elasticity and coefficient of restitution of cornstalk pith, which is more evident in the radial compression test, and the yield strength of cornstalk pith is nearly 10 times that of cornstalk rind, we believe that this is closely related to the microstructure of cornstalk.

3.2. Microstructure Analysis

The SEM image of the cornstalk rind profile was shown in Figure 2. On the SEM image of the outside of the cornstalk rind (Figure 2a), the surface fiber lines can be clearly seen, and there is no special microstructure. On the inside of cornstalk rind (Figure 2b), it can be seen that a large number of tiny pores were distributed on its surface, which is completely different from the respiratory stomata of plant leaves, which also aroused our great interest.

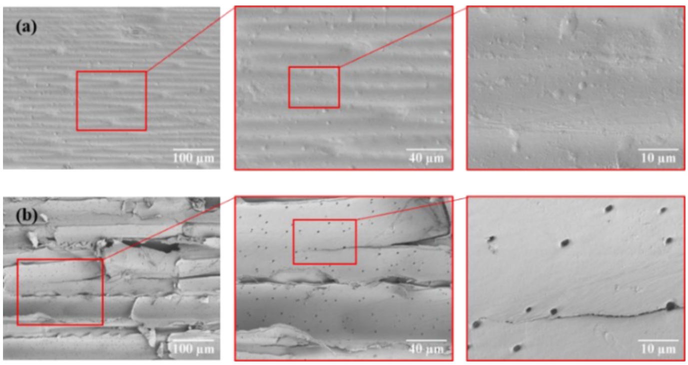

Figure 2. SEM image of cornstalk rind. (a): outside (cornstalk surface); (b): inside.

Similarly, the SEM image of the cornstalk pith section was shown in Figure 3. It can be seen that the microstructure of the cornstalk pith was completely different from the inside microstructure of the cornstalk rind. The specific performance is that the cornstalk pith was a series of staggered cavities on the microscopic scale, and there are also a large number of tiny pores on the surface of the cavity, but the density of the pores was significantly lower than the inside of the cornstalk rind.

We initially think that this is the main reason for the higher yield strength and higher coefficient of restitution of cornstalk pith. When the cornstalk was compressed, the cornstalk rind ruptures along the fiber grain path, when the cornstalk pith was pressurized, the air in the cavity was expelled from the tiny pores. A large amount of discharged air was temporarily stored on the tiny pores of the cornstalk rind, after the load is stopped, the air returns to the cavity along the original path, which makes the cornstalk pith have a higher yield strength and coefficient of restitution. On the other hand, the cavities were arranged in a staggered manner, during the axial com-pression and three-point bending process, the phenomenon of strong damage such as stress concentration is avoided, which leads to the same high bending strength of the cornstalk pith. This is consistent with the results obtained from physical tests of mechanical properties.

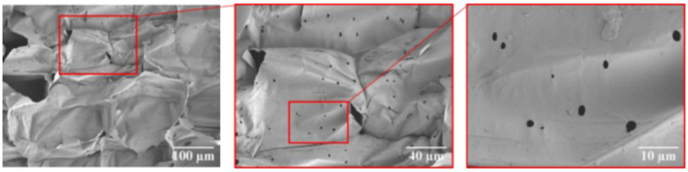

Figure 3. SEM image of cornstalk pith.

The SEM image obtained by scanning electron microscopy (SEM) of the cornstalk section was shown in Figure 4. It can be obviously seen that the section of a single cavity of the cornstalk pith was much smaller than that of a single fiber of the cornstalk rind, and the wall thickness of cornstalk pith cavity was much smaller than that of cornstalk rind fiber. This is also the reason why the yield strength of cornstalk pith is higher than that of cornstalk rind, which is reflected in that even if the small staggered cavities of cornstalk pith were partially damaged, there are enough cavities to support the recovery of the original shape of cornstalk pith, and the rind fiber wall was an integral hollow cylinder with a large cross-section, and the damage of a small part of the fiber wall will directly lead to the overall damage on the macroscopic level.

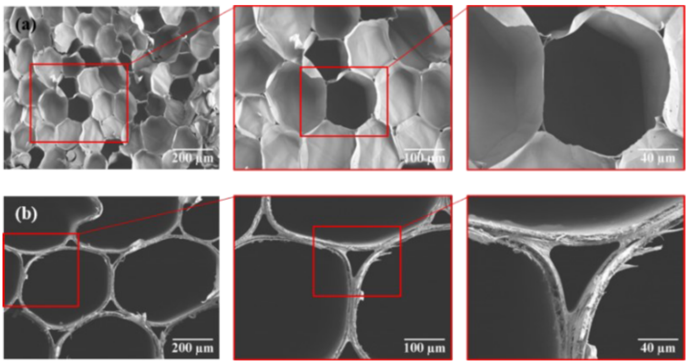

Figure 4. SEM image of cornstalk cross-section. (a): pith; (b): rind.

In terms of cutting mechanical properties, because the cornstalk pith cavity was small and thin-walled, the cornstalk pith can be cutting smoothly and easily by a smaller cutting force during the cutting process. The cornstalk rind fiber wall was thick and the cross-section was large, during the loading process, the fiber wall was usually compressed and deformed until yield rupture, most of the fiber wall was broken, and a large number of fiber walls are tightly packed, continue to load, the entire cornstalk rind to be cut off. In the whole cutting process, yield fracture occurs first and then cut fracture occurs, which is also consistent with the physical cutting test results.

4. Conclusion

The findings of this study can be summarized as follows:

(1) In addition to radial compression, the mechanical properties of cornstalks mainly depend on cornstalk rind.

(2) From the profile SEM images, the outside of the cornstalk rind was smooth, with clear fiber lines, and a large number of tiny pores were distributed on the inside of the cornstalk rind. The microstructure of cornstalk pith was a series of staggered cavities, and a large number of tiny pores were also distributed on the wall of the cavities. Under the action of external load, the air in the cavity of the cornstalk pith spongy tissue flows along the pores of the cavity wall, which reduces the probability of cavity rupture and effectively improves the elasticity and coefficient of recovery of the cornstalk pith.

(3) From the cross-section SEM images, the cornstalk rind was thick-walled and has multiple channels, and each channel has a single cavity. Cornstalk pith was thin-walled, has multiple channels, and each channel was multi cavities, and the cross-section of a single unit was much smaller than that of cornstalk rind. On the microscopic scale, under the same load, cornstalk rind was more easily damaged than cornstalk pith, this is consistent with the macroscopic experimental results that the mechanical properties of cornstalk mainly depend on cornstalk rind.

(4) The study of mechanical properties found that cornstalk rind has outstanding contributions in mechanical strength and other aspects, and cornstalk pith in terms of restitution coefficient. The above conclusions can provide new inspiration for the design of lightweight structural design and engineering biomimetic material preparation.

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